SNUBBER CIRCUIT

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority from copending applications having serial number xx/xxx,xxx (attorney's docket number 200300840-1, entitled "ALTERNATING CURRENT SWITCHING CIRCUIT") and serial number xx/xxx,xxx (attorney's docket number 200311455-1, entitled "POWER CONVERTER") each of which were filed on January 23, 2004 and each of which are hereby incorporated by reference herein.

BACKGROUND

[0002] Alternating Current (AC) circuits comprising inductive loading contain stored energy that, when the circuit is switched off, needs to be dissipated. If this stored energy is not accounted for in the design of the circuit, the result could be a number of undesired effects on the circuit and/or the circuit's surrounding environment.

[0003] One undesired effect on the circuit can be the build-up of heat in a circuit. For example, circuitry utilized in a switching device may heat up. This may result in requiring a designer to include a heat sink for a switching device. The addition of a heat sink may add cost to a design.

[0004] Another undesirable effect on a circuit with stored inductive energy is that the switching-off of the circuit could result in large discharge transients being dissipated throughout the rest of the circuit. These large discharge transients may cause damage to other circuit elements that absorb the energy of the discharge transients.

[0005] Yet, another undesired effect may be radio frequency (RF) emissions over a desired level. Various jurisdictions classify devices and limit the types of devices that can be sold. For example, in the United States, the FCC certifies devices as "Class A" or "Class B" depending on the amount of RF energy that the device emits. "Class B" devices are authorized for home use whereas "Class A" devices are limited to office use.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Embodiments of the present invention will be described by way of exemplary embodiments, but not limitations, illustrated in the accompanying drawings in which like references denote similar elements, and in which:

[0007] FIG. 1 illustrates an AC MOSFET switch, including anti-parallel diodes, in accordance with one embodiment.

[0008] FIG. 2 illustrates a more detailed look at an AC MOSFET switch, including intrinsic parasitic diodes of the MOSFETs, in accordance with one embodiment.

[0009] FIG. 3 illustrates current that is delivered to a load when one embodiment of the AC MOSFET switch is utilized to control current.

[0010] FIGs. 4A-4C illustrate a power filter and its effects on the current drawn by a load driven by an AC MOSFET switch, in accordance with one embodiment.

[0011] FIG. 5 illustrates an AC MOSFET switch design including a snubbing device, in accordance with one embodiment.

[0012] FIG. 6 illustrates a single IC device containing two NMOS type MOSFET devices of an AC MOSFET switch, in accordance with one embodiment.

[0013] FIG. 7 illustrates an imaging device, suitable for housing an apparatus utilizing a snubber circuit, in accordance with one embodiment.

[0014] FIG. 8 illustrates a fuser power control circuit utilizing an AC MOSFET switch including a regenerative snubber, in accordance with one embodiment.

[0015] FIG. 9 illustrates combined snubber and bias circuitry, in accordance with one embodiment.

[0016] FIG. 10 illustrates combined snubber and bias circuitry, in accordance with another embodiment.

[0017] FIG. 11 illustrates a combined snubber and bias circuit, in accordance with yet another embodiment.

[0018] FIG. 12 illustrates a regenerative snubber, in accordance with another embodiment.

[0019] FIG. 13 illustrates a regenerative snubber with additional DC bias, in accordance with another embodiment.

[0020] FIG. 14 illustrates a regenerative snubber in use with a DC-DC converter, in accordance with one embodiment.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0021] Although specific embodiments will be illustrated and described herein, it will be appreciated by those of ordinary skill in the art that a wide variety of alternate and/or equivalent implementations may be substituted for the specific embodiments shown and described without departing from the scope of the present invention. This application is intended to cover any adaptations or variations of the embodiments discussed herein. Therefore, it is manifestly intended that this invention be limited only by the claims.

[0022] The following discussion is presented in the context of MOSFET devices. It is understood that the principles described herein may apply to other transistor devices.

[0023] Refer now to FIG. 1 wherein an AC MOSFET switch **110**, including anti-parallel diodes **112 114**, is illustrated, in accordance with one embodiment. For the MOSFETs **142 144** illustrated, the sources of the MOSFET devices are coupled at junction **102**. In one embodiment, MOSFETs **142 144** are power MOSFETs. In addition, the gates are electrically coupled at junction **104**. These couplings are to facilitate the operation of the two MOSFETs **142 144** as a single AC MOSFET switch. Thus, by applying a gate to source voltage, V_{GS}, greater than the threshold voltage, V_{TH}, to the two MOSFETs **142 144,** both MOSFETs conduct current **120**.

[0024] Also illustrated in FIG. 1 are two diodes **112 114**. These diodes **112 114,** which may be parasitic or explicit, are anti-parallel to their respective MOSFETs. As described in further detail below, these diodes **112 114** may be utilized to bypass the intrinsic anti-parallel diodes of the MOSFETs. Thus, as illustrated, the anodes of the diodes **112 114** are coupled to the sources of the diodes' respective MOSFET and the cathodes are coupled to the respective drains.

[0025] FIG. 1 also illustrates the AC MOSFET switch in use in controlling power to a load. As previously mentioned, AC MOSFET switch **110** comprises two MOSFETs **142 144.** AC MOSFET switch **110** controls current **120** through load **130**. This may be accomplished by switch control circuit **140** which applies the gate-source voltages for the two MOSFETs **142 144** forming the AC MOSFET switch **110**. In the embodiment illustrated, charge pump biasing circuit **150** supplies current to switch control circuit **140** from line (L) **172** and neutral (N) **174** connections of the AC power source.

[0026] FIG. 2 illustrates a more detailed look at an AC MOSFET switch, utilizing P type MOSFETs, including intrinsic parasitic diodes **232 234** of the MOSFETs **242 244**, in accordance with one embodiment. Also illustrated are antiparallel diodes **212 214** which may be utilized to bypass the intrinsic anti-parallel diodes **232 234** of the MOSFETs. Note that the sources of both MOSFETs **242 244** are coupled **204** to each other. In addition, the gates of both MOSFETs **242 244** are coupled **206** to each other. When a voltage, V_{SG} **280** less than a threshold voltage V_{TH} is applied, the MOSFETs **242 244** will be "turned-off" and the internal reverse biased PN junctions will substantially prevent current from flowing through the MOSFETs.

[0027] When a voltage, V_{SG} **280** greater than a threshold voltage V_{TH} is applied to the common sources and gates of MOSFETs **242 244** are turned on to facilitate the flow of current through the AC MOSFET switch. Note that current will flow in the reverse direction in MOSFET **242** or **244** depending on the polarity of the AC voltage source. That is, in the reverse direction as is normally used in DC circuits, that is drain to source in an N type MOSFET or source to drain in a P type MOSFET. The reverse current flow causes no problem as the MOSFET transistor is truly a bidirectional device, that is, current may flow from drain to source or source to drain once the proper gate voltage is applied and the conductive channel forms. Normally, during reverse polarity across the source/drain of a MOSFET, an internal PN junction, represented by parasitic diodes **234** and **232** in FIG. 2, will eventually turn on allowing current **271** to flow. Note that parasitic diodes **234** and **232** are not separate from the MOSFET **244**

and **242**; e.g. parasitic diode **234** is a PN junction that is part of the structure of transistor **244**. Once the gate voltage is removed the parasitic diode conducts during reverse current flow which makes a single MOSFET unsuitable for the control of alternating current **271 273**. The common source configuration of MOSFET **242** and **244** of Fig. 2 results in one of the parasitic diodes in a reverse biased state which substantially prevents current flow through the parasitic diodes **232 234** when the MOSFETs are in either the conducting or nonconducting states.

[0028] Referring again to FIG. 1, switch control circuit **140** and charge pump circuitry **150** are utilized to provide control for the application of the voltage to the gates of MOSFETs **142 144**. In the embodiment illustrated, switch control circuit **140** may be an externally controlled pulse width modulation circuit. In the embodiment illustrated, charge pump **150** utilizes the AC line to power the pulse width modulation circuitry. In addition, the frequency of the modulated control signal may be fixed, whereas the duty cycle of the modulation, as described below, is utilized to determine the power to be delivered to the load **130**. In an alternative embodiment the gate and source of the AC MOSFET may be driven by a circuit which has a minimum conduction time combined with a variable frequency to determine the power to be delivered to the load **130**.

[0029] FIG. 3 illustrates current that is delivered to a load when one embodiment of the AC MOSFET switch is utilized to control current. For example, as discussed above with respect to Figure 1, the switch control circuit **140** may be a pulse width modulation circuit. In such a case, the power delivered to the load **130** can be controlled by changing the duty cycle of the pulse control signal. FIG. 3 illustrates an example input voltage **310** from the line and neutral. Illustrated also, in the dark shaded regions **320**, are the periods where the AC MOSFET switch **110** is switched on to allow current to flow through the load **130**. The voltage **310** and current **320** are normalized so that they share a common envelope. Thus, in the illustrated embodiment, a 50% duty cycle signal driving the gate to source voltage will result in an effective power of one half the total power available being delivered the load. By utilizing a pulse width modulation

technique, the level of power delivered to the load can be adjusted by controlling the width of the pulses generated by the pulse width modulation of the switch control circuit. The equation governing the power transfer to the load is:

$$Pavg = \frac{Vrms^2}{R} \cdot d.$$

Where V_{rms} is the Root Mean Square (rms) voltage of the AC power source, R is the resistance of the load and d is the duty ratio of the pulse width modulator driving the AC MOSFET. By inspection of this equation, the power transferred to the load is a linear function of the duty ratio of the pulse width modulator. The load is at zero power when the duty ratio is zero and at maximum power when the duty ratio is 1.

[0030] In an alternative embodiment in which the gate and source of the AC MOSFET switch are driven by a circuit which has a minimum conduction time combined with a Variable Frequency Oscillator (VFO) the power delivered to the load **130** is determined by

$$P = V^2 \div R \times f \times T_{\min}$$

Where V is the rms voltage of the AC power source, R is the resistance of the load, f the frequency of the VFO driving the AC MOSFET and T_{min} the minimum conduction time allowed. By inspection, this equation shows that the power transferred to the load is a linear function of the frequency of the VFO. The load is at zero power when the VFO frequency is 0 and at maximum power when the period of the frequency of the VFO is equal to or less than the minimum allowed conduction time T_{min}.

[0031] The above examples operate to facilitate the switching of the alternating current at relatively higher frequencies. There are advantages to switching the current at relatively higher frequencies. Switching frequencies out of the audio range (e.g. greater than 20 KHz) can be utilized to reduce human factor issues associated with audible switching noise. Another advantage of operation at higher frequencies may be a reduction in switching and conduction losses. Implementations operating at significantly lower frequencies spend more time in

the linear region of operation. Spending more time in the linear region during switching may dissipate significant amounts of additional energy in the form of heat as relatively slow transitions are made through this linear region. In addition, because of the relatively low voltage drops associated with the disclosed switching of alternating current, less energy is dissipated from the product of the current flowing across the voltage drops of the devices. In addition, the AC MOSFET switching circuit above does not introduce significant harmonics into the alternating current. This can reduce costs associated with filtering these harmonics to meet international regulatory requirements.

[0032] FIG. 4A illustrates input circuitry for an AC MOSFET switch, in accordance with one embodiment. Illustrated is a filter stage **410** to provides a high frequency short to ground to any transients or conducted emissions that occur across the inputs. Illustrated also is a filtering stage **420** to provide smoothing of the alternating current drawn by the load **430**. The effect of this filter is to smooth the harmonic rich current drawn by the pulse width modulated, or VFO driven load, such that the power source experiences a continuous current flow with virtually no harmonic current content.

[0033] In the embodiment, switch control circuit **450** switches the current **472** delivered to the load as illustrated in FIG. 4B. During times of switching, assuming a purely resistive load, the current **472** through the load **430** will follow the line voltage provided, that is, it will be in phase. When the switch is turned off, the current delivered to the load will drop to zero **474**. Thus, as can be seen there will be dramatic shifts or steps in the current drawn by the load as the switch turns on and off. These step changes in the current represent unwanted current harmonics placed on the AC power source which may exceed regulatory limits. To solve this problem, filtering stage **420** is added to the circuit. FIG. 4C illustrates the current drawn from the AC power source at the line and neutral connections by the switched load as a result of the filtering stage **420**. When the switch is turned off, the filtering stage **420** smoothes current **476** drawn by the load **430**. In the case in which the switch is driven by a pulse width modulator, the total instantaneous current drawn by the circuit may be the sum of the

fundamental current and the instantaneous value of the ripple current. This instantaneous current may be expressed as

$$i_L(t) = \frac{V\cdot d}{R}\cdot\sin\left(2\cdot\pi\cdot f_o\cdot t\right) + \frac{\pi^2}{4}\cdot(1-d)\cdot\left(\frac{f_c}{f_s}\right)^2\cdot\frac{V\cdot d}{R}\cdot\sin\left(2\cdot\pi\cdot f_o\cdot t\right)\cdot\sin\left(2\cdot\pi\cdot f_s\cdot t\right).$$

where f_C is the resonant frequency of filtering stage **420**, f_S is the switch frequency of the pulse width modulator, f_O is the frequency of the AC power source, d is the duty cycle of the pulse width modulator, V is the peak source voltage, and R is the load resistance **430.** Under direct examination of this equation it is noted that, as the switch frequency of the pulse width modulator is increased, the resultant alternating current waveform at the Line and Neutral connections smoothes dramatically.

[0034] FIG. 5 illustrates an AC MOSFET switch design including a snubbing device **580**, in accordance with one embodiment. Snubbing device **580** is utilized for dissipating energy stored in the circuit. Stored energy in a circuit exists due to various factors associated with the circuit such as: parasitic inductance associated with the wiring providing the AC current, parasitic inductance in the components leads, and inductance in the load itself. Snubber designs are designed to capture a portion of the stored energy in a circuit, when the circuit is switched off. These snubber designs are to reduce, among other things, the resonance of the circuit. However, these snubber designs are not engineered to dissipate all the energy; they are simply designed to dissipate enough energy to reduce resonance and the resulting resonant “over” voltages that may otherwise occur.

[0035] To dissipate all the energy in the circuit, a significantly larged sized capacitor **573** may be used in snubber **580** design. It is desirable to have the resistance **577** approximately match the resistance in the load **530**. Thus, if the load resistance is approximately 20 ohms, then the resistance of the snubber should be selected to be about 20 ohms. In addition, the stored inductance **575** for a typical circuit driving the AC MOSFET switch has been measured at

approximately 100 nanoHenries. In some snubber designs, a capacitor capable of capturing about 1/5 of the energy stored in the inductive parasitics may be utilized. As mentioned, this capacitor size is utilized to simply avoid resonance of the circuit. However, the remaining energy is dissipated via heat in the switching element or as Radio Frequency (RF) emissions. To avoid this heat or RF emissions, a larger snubber circuit may be utilized.

[0036] In order to have the snubber dissipate substantially all the stored energy of the circuit, the energy dissipated by the snubber should equal the energy stored due to the inductance of the circuit. Thus,

$$1/2\ LI^2 = 1/2\ CV^2 \text{, where } I = V/R$$

$$1/2\ L(V/R)^2 = 1/2\ CV^2$$

Solving for C we find that:

$$C = L/R^2$$

Thus, the capacitor used is directly related to the value of the parasitic inductance.

[0037] Dissipating heat may be undesirable as it may result in damage to the circuit. A solution to this may be to include a heat sink. However, the addition of the heat sink may add cost to the design. In addition, generation of RF emissions may be undesirable as it may result in poor classification during RF certification proceedings for the device containing the AC MOSFET switch. To protect from RF emissions, a shield for the RF emissions may be provided. Again, however, the addition of a shield may add cost to the design.

[0038] Thus, in one embodiment, the capacitor that is part of the snubber illustrated in FIG. 5 is designed to capture substantially all of the stored energy in the circuit associated with the AC MOSFET switch. In this manner, the design of RF shield and the design of any heat dissipating devices may be reduced.

[0039] FIG. 6 illustrates a single integrated circuit (IC) device **600** containing two NMOS type MOSFET devices of an AC MOSFET switch, in accordance with one embodiment. In an alternative embodiment, two PMOS type MOSFET devices

may be utilized in the construction of an AC MOSFET switch. Recall that the two sources from the two MOSFETs are logically coupled to each other in the AC MOSFET switch. By fabricating the two MOSFETs in a single package on an IC, the two MOSFETs may share a common source region **610** on the IC. In the embodiment illustrated in FIG. 6, a common source region **610** is implanted into the die containing the AC MOSFET switch. The sharing of the common source region **610** may allow the use of a single source lead emanating from the package containing the two MOSFETs of AC MOSFET switch. This, in turn, may result in decreased conduction resistance due to the elimination of one source lead and the source lead's associated wire bonding parasitics, such as ohmic resistance from the die to a package lead. For example, in one embodiment, the elimination of one of the source leads may reduce the impedance by 70 milliohms, corresponding to the impedance associated with one of the leads to the AC MOSFET switch.

[0040] 70 milliohms may be a substantial portion of the overall resistance associated with the AC MOSFET switch. For example, assume an R_{DSON} of 100 milliohms for each MOSFET in the AC MOSFET switch. Thus, with a 70 milliohm resistance for each lead for the source and drain, the overall path impedance across the source and drain is 240 milliohms. Two discrete series devices have an effective resistance through the AC MOSFET switch of 480 milliohms. Recall that the external source lead in the AC MOSFET is used for the application of gate bias and as a conduction path for certain types of snubber applications during switch turn off. By design the external source connection **610** has very low current flow and does not introduce series resistance to the AC MOSFET switch when the switch is conducting. This fact allows the conduction resistance of the AC MOSFET switch to be reduced by 140 milliohms, or a reduction in effective resistance 30% by using a common source region on the die of the AC MOSFET and the elimination of one lead. Since the power dissipated is directly related to the resistance, this results in a 15% reduction in power loss, for the embodiment described. Fabrication of the AC MOSFET switch on a single die also allows one of the gate terminals of the discrete implementation to be

eliminated. The result of the common source region and eliminated gate terminal is a four pin device with two high current drain connections and two lower current gate and source connections. One pin of the four pin device is coupled to each of the gates of the two MOSFETs. Another pin is coupled to the common source region , and each of the two remaining pins are coupled to a different one of the drains.

[0041] Thus, embodiments of an AC MOSFET switch design have been disclosed. This design generally allows for faster operation of the AC MOSFET switch to, among other things, allow operation significantly above the audio frequency spectrum (e.g. greater than 20kHz). The AC MOSFET switch operation generally utilizes higher frequencies which, in turn, allows the device to be used in a broad range of AC power control, thus reducing the use of rectification and the resulting induction of harmonics to the power line. These advantages reduce the use of expensive filtering and allow for better operation in environments containing persons such as the home or office environment. The designs may also allow for single IC design of the AC MOSFET switch in many applications. This may reduce the number terminal thus reducing loss due to lead resistance.

[0042] While various circuit elements are illustrated, it is understood by those skilled in the art that equivalent circuit elements can be utilized without altering the spirit of the embodiment disclosed. For example, in the place of a single bias capacitor, multiple parallel capacitors may be utilized to obtain a desired effective capacitance. The term "capacitor" as used herein (in the specification and in the claims) includes its common meaning as understood by those of ordinary skill in the art, i.e. an electronic device with the ability of storing charge, as well as other devices or combination of devices configured to provide the ability to store charges.

[0043] The bias circuitry utilized to drive control circuitry of the AC MOSFET switch may be combined with the snubber circuitry. By combining the bias circuitry with the snubber circuitry, power that may otherwise be wasted in the snubber circuitry may be utilized to drive the control circuitry.

[0044] FIG. 7 illustrates an imaging system **700**, suitable for housing an apparatus utilizing a snubber circuit, in accordance with one embodiment. As illustrated, for the embodiment, imaging system **700** includes processor/controller **702**, memory **704**, imaging engine **706** and communication interface **708** coupled to each other via bus **710**. Imaging engine **706** comprises a fusing subsystem **720** for fusing toner to paper. In addition to fusing subsystem, imaging system may comprise other inductive heating elements or induction motors. Imaging engine **706** is similar to those found in many imaging systems, such as those available from Hewlett Packard Corp. of Palo Alto, CA. Fusing subsystem **720** is connected to an alternating current power source through interface **730**. Fusing subsystem **720** may utilize a snubber circuit as described by the present disclosure.

[0045] Processor **702**, in combination with other portions of the imaging system **700**, can perform various control functions of the fusing subsystem **720**. For example, in one embodiment, processor **702** controls power management of the fusing subsystem **720** to intelligently power down the fusing subsystem when the fuser is not in use. Otherwise, processor **702**, memory **704**, imaging engine **706**, comm. interfaces **708**, and bus **710** represent a broad range of such elements.

[0046] FIG. 8 illustrates a fuser power control circuit utilizing an AC MOSFET switch **840** including a regenerative snubber **810**, in accordance with one embodiment. A control circuit **820**, such as a linear analog pulse width modulator (PWM), controls power delivered to a fusing heating element **830** by an AC MOSFET switch **840**. As the control circuit **820** turns off the AC MOSFET switch **840**, current is diverted through regenerative snubber **810**. Regenerative snubber **810** contains circuitry to generate bias voltage **825**. Thus, in this embodiment, the control circuit **820** is biased via the regenerative snubber **810**.

[0047] Thus, a significant portion of the energy that would otherwise be dissipated as heat in a lossy snubber, e.g. resistor and capacitor snubber, can be "recaptured" and utilized. As illustrated in FIG. 8, the energy can be utilized to bias the control circuit **820**. In other words, the snubber and the bias circuitry can be combined into a single circuit. In addition, depending on the design of the

snubber and bias available from the snubber, other items in a system could be powered via the snubber circuitry. For example, in a device dissipating a large amount of heat which requires a cooling fan, the cooling fan, in addition to or in lieu of the control circuit, could be powered by the regenerative snubber.

[0048] FIG. 9 illustrates a regenerative snubber, in accordance with one embodiment. MOSFETs Q1 **942** and Q2 **940** and their corresponding explicit anti-parallel transistor diodes **928 918** form an AC MOSFET switch as previously described. When the current *i* **990** flows as illustrated, and Q1 **942** and Q2 **940** are turned off, e.g. the circuit enters a turn-off state, the current is diverted through energy storage device C_1 **910** and capture circuitry R_1 **912** and d_2 **914**. This diversion causes charge to build on an energy storage device, bias capacitor C_3 **916**. Bias capacitor C_3 **916** provides a bias voltage between a bias node **905** and a ground **950** for the bias circuit. Current then continues through explicit transistor diode **918** of Q_2 **940**. When Q1 **942** and Q2 **940** are turned back on, C_1 **910** is reset. That is, the charge stored on C_1 **910** is discharged by flowing through Q1 **942**, d_1 **970** and is then dissipated in R_1 **912**.

[0049] The symmetry of the snubber/biasing circuit allows for the charge to occur with both directions of AC flow. When the current **990** is reversed and Q_1 **942** and Q_2 **940** are turned off, the flow is through devices C_2 **920**, R_2 **922**, d_3 **924**, charging C_3 **916** and then through explicit transistor diode **928** of Q_1 **942**. When Q_1 **942** and Q_2 **940** are turned back on, C_2 **920** is reset and the charge stored on capacitor C_2 **920** flows through MOSFET Q_2 **940**, d_4 **972** and is dissipated in R_2 **922**. Thus, during the turn-off period of the AC MOSFET switch, charge is supplied to bias capacitor C_3 **916** resulting in bias voltages at bias node **905**. The voltage between the ground **950** and bias node **905** provides bias for the control circuit.

[0050] FIG. 10 illustrates a regenerative snubber, in accordance with another embodiment. Capacitor C_3 **1016**, stores charge that can be utilized to bias a control circuit. When MOSFETs Q_1 **1042** and Q_2 **1040** are turned off, the current *i* **1090** flows through C_1 **1010** and d_2 **1014** and charges C_3 **1016**. The current continues through explicit transistor diode **1018** of Q_2 **1040**. In this embodiment,

there is no resistor in the turn-off circuit to dissipate energy. Thus, during turn off, more energy may be delivered to charge C_3 **1016.**

[0051]When MOSFETs Q_1 **1042** and Q_2 **1040** are turned on, C_1 **1010** resets through Q_1 **1042**, d_1 **1070** and R_1 **1012**. When current *i* flow **1090** reverses, similar results occur through snubbing/biasing devices C_2 **1020**, R_2 **1022**, d_4 **1072**, explicit transistor diode **1028** and d_3 **1024**.

[0052]FIG. 11 illustrates a regenerative snubber, in accordance with yet another embodiment. By modifying the embodiment of FIG. 10, and replacing the resistors with inductors L_1 **1113** and L_2 **1123**, the energy loss during reset can also be greatly reduced allowing significantly more of the snubbed energy to be captured and pumped to C3 **1116**. When Q_1 **1142** and Q_2 **1140** are turned off, capacitor C3 **1116** is charged through either C_2 **1120** and d_3 **1124** or C_1 **1110** and d_2 **1114**, as previously discussed, depending on the current direction through the MOSFETs at the time of the turn off. Assume current flow *i* **1190**, when Q_1 **1142** and Q_2 **1140** are turned on. The charge stored on C_1 **1110** causes current to flow through L_1 **1113**. The L_1C_1 circuit will resonate at a frequency which may be expressed as

$$\omega_0 = 1/2\pi\sqrt{L_1C_1}$$

To provide adequate snubber reset, the resonant frequency of L1 C1 and L2 C2 can be chosen such that the frequency is at least as high as the minimum period expected for conduction Q1 **1142** and Q2 **1140**.

[0053]When Q_1 **1142** and Q_2 **1140** turn on the resonance of L1 C1 results in an attempt to invert the voltage on C_1 **1110**. When the voltage at the anode to d_2 **1114** reaches a potential just above that of bias node **1105**, d_2 **1114** switches on allowing additional energy to pump into C3 **1116**. This embodiment advantageously reduces the amount of energy loss by removing resistors from both the turn-off and reset operation of the snubber/bias circuit.

[0054]Also illustrated in FIG. 11 are snubbers for the active devices of the snubber/bias circuitry. The circuit contains a number of diodes which may themselves be a source of conducted and radiated emission to the circuit. In

order to facilitate the reduction of these conducted and radiated emissions, RC snubber circuits **1180** can be placed across the diodes.

[0055] In one embodiment, fast switching diodes are utilized in the snubber/biasing circuit. For example, diodes with switching time of 10 ns or faster may be utilized in one embodiment.

[0056] When the AC MOSFET is switching, levels of bias current provided by the circuit will be at relatively high levels compared to when the AC MOSFET is not switching. For example, assuming the AC MOSFET switch is operating at 28.5 kHz, with a line voltage of 120 V_{RMS} and 0.01 μFarad capacitance for C_1 and C_2. Each of the snubber capacitors effectively "sees" the RMS voltage across it with C_1 **1110** seeing the first half cycle and C_2 **1120** seeing the second half cycle. The snubber capacitors are charging and discharging at the switch frequency. The current available to charge C_3 can be calculated as follows:

$$Q = i \times t = c \times v \quad => \quad i = {(c \times v)}/{t} = c \times v \times f$$

$$i = (0.01 \times 10^{\ 6})(120)(28500)$$

$$i = 34.2 \text{ mA}$$

This value may be doubled in the embodiment in which an inductor is used to invert the voltage of the snubber capacitor during snubber reset.

[0057] However, when the AC MOSFET switch is idle, the switching of the snubber circuit occurs with the line frequency of, for example, 50-60 Hz. In this case, the capacitor C3 **1116**, which see the peak value of V, will have much less current to charge it:

$$i = (0.01 \times 10^{\ 6})(120 \times \sqrt{2})(60)$$

$$i = 0.10 \text{mA}$$

[0058] FIG. 12 illustrates a regenerative snubber, in accordance with another embodiment. In this embodiment, two series resistors R_3 **1282** and R_4 **1284** are added along with a full waver rectifier **1280**. These elements may be utilized to help provide additional DC bias. This additional DC bias may be useful, when the circuit is idle, in supplying additional charge to bias capacitor C_3 **1216**. For

example, as previously noted, assuming a power source of 120 VAC_{RMS}, the resistors R_3 **1282** and R_4 **1284,** at 60 kΩ, provide an additional:

$$(120)/(60k) = 2.0 \text{ mA}$$

Thus, by placing the full wave rectifier **1280** and series resisters R_3 **1282** and R_4 **1284** in the circuit as illustrated, the current available to the capacitor C_3 **1216** for providing bias to the control circuitry, while the AC MOSFET switch is idle, can be increased from 0.1 mA to 2.1 mA.

[0059] FIG. 13 illustrates a regenerative snubber with additional DC bias, in accordance with another embodiment. In the circuit, in addition to the current supplied by capacitors C_1 **1310** and C_2 **1320,** to charge C_3 **1316,** resistors R_1 **1388** and R_2 **1386** are utilized to provide increased current to charge C_3 **1316.** Similar to the calculations above, utilizing 60 kΩ resistors for R_1 **1388** and R_2 **1386** results in an additional 2.0 mA of current being available. This increases the bias current to 2.1 mA.

[0060] Also illustrated in FIG. 13 is the use of a zener diode **1384** across C_3 **1316.** It is possible that the energy stored on C_3 **1316** may cause the voltage at the V_{BIAS} node **1305** to rise to levels that exceed what is allowed by a control circuit biased by the regenerative snubber. In this case, by placing a zener diode **1384** with the proper breakdown voltage across the capacitance device C_3 **1316**, a proper voltage value can be maintained at the bias node **1305**. For example, if a V_{BIAS} value for a control circuit of 13 volts is desired, a zener diode with a 15 volt breakdown voltage can be placed across the capacitance device C_3 **1316** to ensure that the voltage level across C_3 **1316** does not exceed 15 volts. In an alternative embodiment, a resister is placed across C_3 **1316** to facilitate maintenance of a voltage across C_3 **1316**. In another embodiment an avalanche diode is utilized to ensure that a proper voltage value may be maintained at the bias node **1305**.

[0061] While the previous embodiments illustrate a regenerative snubber in use with the AC MOSFET switch, the regenerative snubber may be used in other configurations. FIG. 14 illustrates a regenerative snubber in use with a DC-DC converter, in accordance with one embodiment. Illustrated in FIG. 14 is an

electrically isolated flyback converter. Power switch **1430** is utilized to control power delivery to the load **1425**. Power switch **1430** is controlled by control circuit **1470**. Control circuit **1470** is biased by bias node **1405** charged by regenerative snubber **1440**. While an electrically isolated flyback converter DC switching circuit is illustrated in conjunction with the regenerative snubber, other DC switching circuit types such as boost and buck-boost converters may be utilized.

[0062] Regenerative snubber **1440** is utilized to capture energy stored in the electrically isolated flyback converter when power switch **1430** is switched off. When power switch **1430** turns off, current i **1490** flows through C_1 **1410** and d_1 **1414** and charges C_3 **1416** and thus corresponding bias node **1405**. When power switch **1430** turns on, C_1 **1410** resets through power switch **1430**, d_2 **1419** and L_1 **1418**.

[0063] During low frequency operation of the DC-DC switching circuit, sufficient current to provide adequate bias may not be provided by C_1 **1410**. Thus, resistor R_1 **1412** is coupled across C_1 **1410** to provide additional bias. An appropriate value of R_1 **1412** for providing adequate bias current for bias node **1405** may be application dependant.

[0064] Thus, a unique method of providing bias for a control circuit is provided. Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that a variety of alternative and/or equivalent embodiments may be substituted for those disclosed herein without departing from the spirit and scope of the claimed subject matter. This application is intended to cover any adaptations or variations of the preferred embodiments discussed herein. Therefore it is intended that the present invention be limited only by the claims and the equivalents thereof.